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Mycotoxin risks in Mediterranean agroecosystems: the maize paradigm linking plant health, climate change, and food/feed chains

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Summary. Mycotoxin contamination is a major concern for food and feed safety, particularly in Mediterranean agroecosystems, where climatic variability strongly affects fungal ecology and crop susceptibility. This paper reconsiders, mycotoxin-producing fungi from a plant health perspective, framing contamination as the outcome of interactions among host plants, fungus communities, and environments. Multiple fungal species often co-exist, resulting in frequent co-occurrence of mycotoxins and complex contamination patterns. Maize was assessed as a paradigmatic system, highlighting the close links between plant infections, feed contamination, and food safety. These links include carry-over metabolism of aflatoxin B1 into aflatoxin M1, following ingestion of contaminated feed by dairy cows, and excretion of aflatoxin M1 in milk. Climate change can further modify these dynamics, by reshaping ecological niches, increasing crop stress, and causing shifts in fungal communities, with consequences for both the intensity and distribution of mycotoxin contamination. Mycotoxin risk is a dynamic, system-level issue, affecting entire food/feed chains. Addressing this complexity requires integrated approaches, that combine plant health management, monitoring, and predictive modelling to support risk assessment under changing environmental conditions.

Keywords. Fungal ecology, crop contamination, maize systems, multi-mycotoxin co-occurrence, food chain risk.

MYCOTOXIN-PRODUCING FUNGI AS PLANT HEALTH ISSUES IN MEDITERRANEAN AGROECOSYSTEMS

Mycotoxin contamination is widely recognized as a major chronic concern for human food and animal feed safety, also causing acute toxicity in some geographic areas where exposure to high toxin concentrations still occurs. Reported effects ranges from carcinogenicity to immunosuppression, with liver and kidney organs being mainly affected (Shekhar *et al.*, 2025; Thierry *et al.*, 2026).

The Mediterranean scope of this review refers to crop-production systems located within the Mediterranean basin, including European and North African areas sharing broadly comparable agroclimates, although with substantial local variability. These agroecosystems are characterized by hot and dry summers, recurrent droughts, irregular rainfall distribution, and marked interannual climate variability. The main crop systems at risk include cereals, particularly maize and small grains, as well as nuts, grapes, apples, and other fruit crops. Ongoing climate change is amplifying historical climatic constraints, through increasing temperatures, more frequent heat and water stress, altered precipitation patterns, and increased frequency of extreme events, thereby modifying host plant susceptibility, fungal ecology, and mycotoxin risks (Casu *et al.*, 2024).

Fusarium, *Aspergillus* and *Penicillium* are the genera most frequently associated with mycotoxin-producing species. Based on recent reports, *Claviceps* and *Alternaria* should be added, because their metabolites are listed among mycotoxins that are regulated or are candidates for regulation.

Most mycotoxin-producing fungi are weak parasites and their main impacts on agricultural products are not, or are only partially due, to crop yield reductions, but rather involve cryptic health risks for grain consumers. Symptomless contamination, where grain and fruit are apparently healthy, can also be sources of these toxic metabolites.

Since the last decades of the 20th century, mycotoxins have progressively shifted from being viewed as chemical contaminants of agricultural commodities to being understood as biological outcomes of processes within cropping systems, as results of plant-fungi-environment interactions. This change reflects recognition that contamination largely originates during crop development, where toxigenic fungi can colonize susceptible plants under suitable conditions, rather than arising solely during grain storage or processing (Palumbo *et al.*, 2020).

Mycotoxins are secondary metabolites produced by filamentous fungi infecting many crops, particularly staple cereals and nuts (Mafe and Büsselberg, 2024). However, recent research has shown that some mycotoxins may also play roles in plant-pathogen interactions (Righetti *et al.*, 2019; Armer *et al.*, 2024).

In agricultural environments, crops are exposed to diverse fungal communities rather than to individual pathogens; particular species may produce multiple toxins, and the same mycotoxin can be synthesised by different fungi. Co-occurrence of different mycotoxins is common, making these fungi-crop-environment interactions persistent public health and economic problems

(Palumbo *et al.*, 2020). Human and animal exposure may also occur through multiple dietary sources that are often symptomless, resulting in high probability of exposure.

Mycotoxin contamination is sensitive to climatic variability. Temperature, water availability, and crop stress are key drivers regulating these processes. Increased temperatures, altered precipitation patterns, and increasingly frequent extreme climatic events are modifying plant disease dynamics and reshaping agroecosystems, with implications that extend beyond crop yields to encompass food safety and food security (IPCC, 2022). Ongoing climate change will affect the prevalence and distribution of toxigenic fungi, and is likely to continue affecting mycotoxin risk (Casu *et al.*, 2024).

Consistent with this view, reports indicate that mycotoxin contamination is emerging or becoming more relevant in areas where it was previously ignored; climate change is redistributing and intensifying existing risks rather than introducing new hazards (Battilani *et al.*, 2016; Moretti *et al.*, 2019). These changes may ultimately affect crop productivity and food availability and access, and stability within food systems (Weaver *et al.*, 2021; Foini *et al.*, 2023).

From biological perspectives, the *Aspergillus*, *Fusarium*, *Penicillium*, *Alternaria* and *Claviceps* fungi that produce mycotoxins have distinct ecological requirements, and respond differently to environmental drivers (Bennett and Klich, 2003; Lee and Ryu, 2017). This diversity and fungus–host associations result in a wide range of susceptible crops and agroecosystems in which contamination can develop. Shifts in species prevalence have been observed in Europe, including changes in *Fusarium* species occurrence, and increasing relevance of *A. flavus* far from the tropical-subtropical areas where it was commonly reported, under hot and dry conditions (Nielsen *et al.*, 2011; Battilani *et al.*, 2016; Logrieco *et al.*, 2021). These observations emphasize the close links between evolving agroecological conditions and mycotoxin risks.

Taken together, these findings support a reframing of mycotoxin-producing fungi as components of plant disease systems, with direct implications for the resilience of agri-food production chains. Addressing mycotoxin impact, therefore, requires food system approaches that integrate management of all the components of crop value chains, within a food and feed safety perspective, focusing on infection processes in the field as starting points for risk evaluation (Munkvold *et al.*, 2018).

This view is particularly relevant for Mediterranean agroecosystems, where crop production is already affected by recurrent drought, high temperatures, and strong interannual climatic variability, conditions known to favour several toxigenic fungi and to modulate toxin

production. Climate projections indicate that these environmental factors are likely to intensify in the region, potentially increasing frequency of environments conducive to fungal contamination and altering established host–fungus relationships (Raza and Bebbler, 2022; Casu *et al.*, 2024). The Mediterranean basin is a vulnerable area, and is key setting where links among plant health, climate pressure, and food-feed safety can be investigated within an integrated agroecological framework.

The ecological characteristics and host associations of the main mycotoxin-producing fungi occurring in Mediterranean cropping systems are discussed in the following section, with a focus on their interactions with crop systems and environmental conditions.

MYCOTOXIN-PRODUCING FUNGI IN
MEDITERRANEAN CROPPING SYSTEMS:
ECOLOGICAL TRAITS AND HOST ASSOCIATIONS

In Mediterranean cropping systems, occurrence of mycotoxin contamination reflects the coexistence of fungal species with contrasting ecological strategies that exploit different crops, infection windows, and environmental niches. These include *Fusarium* species typically associated with temperate climates, *Aspergillus* species favoured by warm and dry conditions, and several other fungi whose importance varies according to crop and production environments (Bennett & Klich, 2003).

Species of *Fusarium* are among the most important mycotoxin-producing fungi associated with cereals in temperate and Mediterranean agroecosystems. Several species complexes infect wheat and maize, and are responsible for the production of major mycotoxins including trichothecenes, fumonisins, and zearalenone,

as outlined in Table 1 (Bottalico and Perrone, 2002; Goswami and Kistler, 2004). Infections typically occur during sensitive crop stages such as flowering and grain development, when environmental conditions favour fungal colonization (Goswami and Kistler, 2004). The coexistence of multiple fungus species and chemotypes within cereal production systems contributes to the variability of toxin profiles observed in contaminated grain (Leslie and Summerell, 2006).

Species of *Aspergillus* are generally associated with warm environments, and are particularly adapted to elevated temperatures and limited water availability (Klich, 2007; Magan *et al.*, 2011). Among them, *A. flavus* is the principal producer of Afs, and is an important toxigenic fungus affecting maize and other susceptible crops, particularly nuts, in warm agroecosystems (Cotty and Jaime-Garcia, 2007). These fungi can infect crops from flowering onwards, colonising developing kernels in the field, and may also be active in postharvest periods, being well adapted to low water activity (Klich, 2007).

Species of *Penicillium*, *Alternaria*, and *Claviceps* also cause mycotoxin contamination in agricultural systems. Several *Penicillium* species are associated with stored commodities, although infections typically originate in the field, and these fungi produce mycotoxins such as ochratoxin A (OTA) and patulin (Pitt and Hocking, 2009). *Alternaria* species are widespread plant-associated fungi capable of colonizing crops in the field and during post-harvest stages, and of producing a range of emerging mycotoxins, including alternariol (ALT), alternariol monomethyl ether (AME), and tenuazonic acid (TeA) (Maldonado Haro *et al.*, 2023). In contrast, species of *Claviceps* are specialized pathogens that infect reproductive structures of grasses and cereals, and these fungi produce ergot alkaloids, that have been associated with contamination of

Table 1. Major and selected mycotoxins, their producing fungal species, and corresponding acronyms. This information is adapted from Bottalico and Perrone (2002), Goswami and Kistler (2004), Bennett and Klich (2003), Pitt and Hocking (2009), and Lee and Ryu (2017).

Mycotoxin [†]	Produced by	Acronym
AFs (B1, B2, G1, G2)	<i>Aspergillus flavus</i> , <i>A. parasiticus</i>	AFB1, AFB2, AFG1, AFG2
Ochratoxin A	<i>Penicillium verrucosum</i> , <i>P. nordicum</i> , <i>A. ochraceus</i> , <i>A. carbonarius</i>	OTA
Fumonisin (B1, B2, B3)	<i>Fusarium verticillioides</i> , <i>F. proliferatum</i>	FB1, FB2, FB3
Zearalenone	<i>F. graminearum</i> , <i>F. culmorum</i>	ZEN
Trichothecenes (B: Deoxynivalenol)	<i>F. graminearum</i> , <i>F. culmorum</i>	DON
Patulin	<i>P. expansum</i>	PAT
Trichothecenes (A: T-2, HT-2)	<i>F. langsethiae</i> , <i>F. sporotrichioides</i>	T2, HT2
Enniatins	<i>F. tricinctum</i> , <i>F. avenaceum</i>	ENNs
Ergot Alkaloids	<i>Claviceps purpurea</i>	EAs
Alternaria toxins	<i>Alternaria</i> spp.	ALT, AME, TA

[†] Major regulated and selected additional compounds relevant for co-occurrence

Table 2. Crop-mycotoxin associations in Mediterranean agroecosystems, indicating commonly reported, minor relevance, and recently reported contamination patterns across different crops, based on literature evidence from Mediterranean and comparable agroecosystems. The main supporting references are reported in the accompanying text. X: Commonly reported; O: Minor relevance; =: Recently reported.

Crop type	Mycotoxin category				
	AFs	Fumonisin	Trichothecenes	Ochratoxins	Patulin
Small grain			X	X	
Maize	X	X	X	X	
Nuts	X			X	
Fresh fruits	=	=		O	X
Grapes	O			X	O
Apple					X

grain crops, particularly rye (Bennett and Klich, 2003).

Ability of mycotoxin-producing fungi to colonize multiple hosts, to persist in soil or crop residues, and to respond to environmental stress, make these fungi recurrent components of Mediterranean cropping systems. Different genera are associated with distinct crops and toxin profiles. Complementing the overview of mycotoxins and producing fungi provided in Table 1, Table 2 summarizes the main crop-mycotoxin associations relevant for Mediterranean agroecosystems. The classification is based on literature evidence from Mediterranean and comparable agroecosystems, and distinguishes between associations that are commonly reported, of minor relevance, or recently reported. “Commonly reported” indicates associations frequently documented for a particular crop, “minor relevance” refers to associations reported less consistently or generally considered of secondary importance, and “recently reported” identifies associations that have emerged or gained attention in recent studies. The associations summarized in Table 2 are supported by literature on mycotoxin occurrence and fungal ecology in cereals, maize, nuts, grapes, apples, and other fruit crops (Bottalico and Perrone, 2002; Cotty and Jaime-Garcia, 2007; Pitt and Hocking, 2009; Palumbo *et al.*, 2020; Leite *et al.*, 2021; Carbonell-Rozas *et al.*, 2024; Casu *et al.*, 2024).

Maize is a paradigmatic crop in Mediterranean agroecosystems, combining the coexistence of multiple toxigenic fungi, frequent mycotoxin co-occurrence, and a central role in food and feed chains.

THE MAIZE PARADIGM: A FOOD-FEED INTERFACE

Maize is a key system in the context of mycotoxin contamination, as this crop embodies the close inter-

connection between plant health, animal nutrition, and human food safety (Leite *et al.*, 2021). This derives from the dual role of maize grain as a major commodity for direct human consumption, and, more critically, as the primary energy source in livestock diets, particularly in intensive milk production systems (Klopfenstein *et al.*, 2013; Erenstein *et al.*, 2022). This dual role makes maize a key vector for mycotoxin transfer in human and animal food systems, amplifying the relevance of even low or subclinical levels of contamination at primary crop production and grain storage stages.

Maize as a key system

Vulnerability of maize to mycotoxin contamination results from plant biology, crop cultivation practices, and environmental exposure (Focker *et al.*, 2023). Maize is a host for a range of weakly pathogenic or opportunistic fungi, that exploit physiological stress conditions and physical damage to colonize kernels (Bryła *et al.*, 2022). Infection processes are often facilitated by biotic factors, including insect activity (e.g., kernel-boring pests), which create entry points for fungi, as well as abiotic stresses, including drought, high temperatures, and nutrient imbalances, all of which compromise plant defenses.

A distinctive feature of maize production are overlaps between crop phenology and environmental conditions that are conducive to fungus development. During flowering and grain filling, the maize crops are susceptible to *Fusarium* infections, especially in temperate and Mediterranean environments (Cao *et al.*, 2014). These lead to accumulation of fumonisins (FBs), DON, and ZEN, depending on the dominant mycotoxin-producing fungus, that is also affected by particular meteorology. In contrast, in warm and dry environments, or during seasons characterized by heat and water stress to plants, *A. flavus* is increasingly competitive, colonizing kernels pre-harvest from silk emergence, and continuing to develop until harvest, and, under favourable conditions, into post-harvest phases (Massomo, 2020). AF production may begin during crop ripening but typically reaches maximum levels after physiological maturity, particularly when kernel moisture drops below 30% (approx. water activity = 0.95) (Giorni *et al.*, 2016).

This ecological duality makes maize a unique substrate where complex fungal communities can establish, depending on small shifts in environmental conditions. As a consequence, maize fields can be dynamic ecological systems in which mycotoxin risk profiles are not static but evolve, in response to climate variability, agronomic practices, and crop management decisions. This is particularly relevant in the Mediterranean basin, where

increasing climate instability is favoring coexistence, and the alternative dominance, of *Fusarium* and *Aspergillus* species within individual crop growth seasons (Camardo Leggieri *et al.*, 2020; Casu *et al.*, 2024).

The role of maize as a key system is further reinforced by its extensive use for production of animal feed (Ogunade *et al.*, 2018). In dairy production, maize is consumed in multiple forms, including grain, high-moisture corn, and, most importantly, silage (Lapris *et al.*, 2025). Maize silage is a key feeding system for ruminant diets, due to its high nutritional value and digestibility (Rocchetti *et al.*, 2022). However, the ensiling process does not eliminate mycotoxin-related risks (Gallo *et al.*, 2021). While fermentation dominated by lactic acid bacteria can inhibit the growth of many spoilage microorganisms (Okoye *et al.*, 2023), it has limited impacts on pre-formed mycotoxins, which are generally stable under silage conditions.

Stability of mycotoxins after ensiling has not been extensively studied (Wambacq *et al.*, 2016). In particular, concentrations of DON and ZEN do not exhibit consistent trends following ensiling, which aligns with their typical pre-ensiling production by *Fusarium* species, and their subsequent persistence in silage. In contrast, mycotoxins including roquefortine C, PAT, cyclopiazonic acid, and mycophenolic acid, primarily associated with *Penicillium* spp., tend to increase in occurrence and concentration after ensiling, likely reflecting the adaptability of these fungi to storage conditions. Conversely, ENNB and AME have reduced average levels and detection frequencies post-ensiling. For other mycotoxins, including FB1, nivalenol, T-2 toxin, AFB1, and OTA, changes associated with ensiling are less clearly defined (Wambacq *et al.*, 2016). This variability may be due to differences in fungal ecology, as *Aspergillus* species can produce AFB1 during storage, whereas FB1 and nivalenol are predominantly synthesized by *Fusarium* species prior to ensiling.

Poor ensiling practices, such as inadequate compaction, oxygen infiltration, or suboptimal fermentation, can create niches for growth of additional fungi, including *Penicillium* and other storage-associated genera, potentially leading to the production of further secondary metabolites (Snelling *et al.*, 2023). Thus, maize should not be viewed merely as a raw commodity, but as a dynamic system in which contamination can originate, persist, and even diversify along the grain production and storage chain.

Multiple fungi and toxin co-occurrence

A challenging aspect of mycotoxin contamination in maize grain is the frequent and complex co-occurrence of

multiple fungal species (Giorni *et al.*, 2009, 2016; Camardo Leggieri *et al.*, 2019; Gallo *et al.*, 2021; Weaver *et al.*, 2021; Rocchetti *et al.*, 2025). This leads to accumulation of multiple mycotoxins within individual maize batches, possibly at low to moderate concentrations, but with significant cumulative relevance (Palumbo *et al.*, 2020; Vandicke *et al.*, 2021; González-Jartín *et al.*, 2022). Modified or masked mycotoxins (Rychlik *et al.*, 2014), formed through plant metabolism or food processing, may also add complexity, as these may not be detected by conventional analytical methods but can be hydrolysed during animal digestion, releasing parent toxins and causing similar toxicities (Freire and Sant'Ana, 2018).

A comprehensive survey of mycotoxin occurrence in maize silage was outlined by Reisinger *et al.* (2019). They collected and analyzed 158 maize silage samples from European dairy cattle farms, revealing the presence of emerging mycotoxins (e.g., emodin, culmorin, ENNs, beauvericin) in more than 70% of the samples assessed. Additionally, among the regulated toxins, DON and ZEN were most frequently detected (68%). These authors also highlighted the potential relevance of mycotoxins for bovine gut health, a previously neglected target for ruminants.

Similar patterns of multi-mycotoxin co-occurrence have also been reported in food commodities intended for human consumption. This highlights the broad relevance of this issue across the human food chain (Palumbo *et al.*, 2020; De Santis *et al.*, 2021).

Toxicological implications of mycotoxin mixtures are still incompletely understood, but this is a recognized and critical gap in current risk assessment (Weaver *et al.*, 2021). Studies have indicated that mycotoxins can interact at multiple biological levels, including maintenance of intestinal barrier integrity, immune modulation, oxidative stress pathways, and endocrine regulation (Gao *et al.*, 2020; Khan *et al.*, 2024; Catellani *et al.*, 2025). In dairy cattle, chronic exposure to multi-mycotoxin mixtures (even at concentrations below regulatory limits) has been associated with subclinical effects including reduced feed intake, impaired nutrient utilization, altered rumen microbiota, and decreased productive performance (Gallo *et al.*, 2020; Akinmoladun *et al.*, 2025). From systems perspectives, toxin co-occurrence challenges the traditional paradigm of single-toxin regulation, and has resulted in calls for more holistic approaches that consider combined effects of multiple contaminants. In maize-based systems, this is particularly relevant because maize is a major contributor to total dietary exposure in animals, and, in some geographic regions, for humans (Battilani *et al.*, 2020; Palumbo *et al.*, 2020; De Santis *et al.*, 2021).

Carry-over to food: the case of AF M1

The transition from animal feed contamination to human food safety risk is clearly shown for the carry-over of AFs into milk. Among the mycotoxins associated with maize, AFB1 is of particular concern due to its high toxicity, its classification as carcinogenic to humans (Group 1) by the International Agency for Research on Cancer (IARC Working Group on the Evaluation of Carcinogenic Risks to Humans *et al.*, 2002), and its efficient metabolic conversion in lactating animals (Zentai *et al.*, 2023).

Following ingestion of contaminated feed, AFB1 is absorbed in animal gastrointestinal tracts, and is transported to the liver, where it undergoes biotransformation mediated by cytochrome P450 enzymes. This process results in formation of several metabolites, including AFM1 (Masoero *et al.*, 2007), which retain significant toxicological activity. The AFM1 is subsequently excreted into milk, typically within hours of animal exposure, establishing rapid and direct links between feed contamination and human dietary intake (Costamagna *et al.*, 2019). The efficiency of this carry-over process is influenced by multiple factors, including level of AFB1 in the animal, duration of exposure, and animal species, breed, health status, and milk yield.

High-producing dairy cows exhibit higher transfer rates than low producers, making modern intensive production systems particularly sensitive to this issue (Bervis *et al.*, 2021). Even when AFB1 levels in feed comply with regulatory limits, resulting AFM1 concentrations in milk may approach or exceed maximum permitted levels, especially under conditions of chronic exposure. From a technological standpoint, AFM1 is an important challenge due to its stability (Iha *et al.*, 2013). This toxin is only partially reduced during pasteurization, and remains largely unaffected by subsequent ultra-high temperature treatments.

During cheese production, AFM1 can partition into curd, leading to higher concentrations in cheese compared to the original milk (Pietri *et al.*, 2016). This persistence underscores the limited effectiveness of downstream interventions and reinforces the importance of controlling contamination at animal feed levels.

Evidence from the Mediterranean region further confirms the relevance of aflatoxin carry-over along feed-to-milk production chains. A recent 20-year review on AFM1 occurrence in milk and dairy products across Mediterranean countries reported overall occurrence frequency of approx. 40%, with contamination levels generally greatest in the southeastern Mediterranean basin, highlighting the persistent exposure risk for consumers in this region (Malissiova *et al.*, 2024). Fur-

thermore, data from Northern Italy, one of the most important dairy-producing areas within the Mediterranean region, provide direct evidence of the relationship between feed contamination and AFM1 occurrence in milk. Ferrari *et al.* (2023) analysed 95,882 raw milk samples collected between 2013 and 2021, and reported that only 0.7% of these exceeded the European regulatory limit of 50 ng L⁻¹. The study also demonstrated a clear association between AFB1 contamination in animal feed materials and AFM1 occurrence in milk, confirming the importance of integrated monitoring strategies throughout the dairy production chain. Similar findings were reported by Serraino *et al.* (2019), who documented the continuous occurrence of AFM1 in more than 31,000 milk samples collected from major Italian dairy processors, despite the generally high compliance with European safety standards.

Beyond aflatoxins, accumulating evidence indicates that other mycotoxins, including those produced by *Fusarium* spp. as well as emerging mycotoxins, can also be transferred into animal-derived products, although generally at low carry-over rates (Seeling *et al.*, 2006; Flores-Flores *et al.*, 2015; Serraino *et al.*, 2019). Nevertheless, the AFB1–AFM1 pathway remains the most well-characterized and regulatory-relevant example, serving as a model for understanding broader implications of animal feed to human food transfer. Altogether, maize shows how mycotoxin contamination is not confined to crop production, but is a systemic challenge that spans plant health, animal metabolism, and human food safety, thus underlining the One Health concept. Its role within the food–feed interface highlights the need for integrated risk assessments and management strategies, capable of addressing contamination as dynamic and multi-layered processes rather than as series of isolated events.

CLIMATE CHANGE AS A RISK AMPLIFIER: IMPLICATIONS AND RESEARCH PRIORITIES

Building on the system perspective outlined in the previous sections of the present review, where mycotoxin contamination results from interactions between fungal ecology, host plant susceptibility, and environmental conditions, climate change is likely to be a major driver for reshaping these processes. Climate effects extend beyond simple increases in temperature or drought frequency, acting instead at system level by modifying ecological niches, host–fungus relationships, and temporal dynamics of infection and toxin production. Heat and water stress enhance the competitiveness of several toxigenic fungi, with *A. flavus* being an emblematic case.

However, further changes are expected, including fungal acclimatization to new environmental conditions and increased aggressiveness (Casu *et al.*, 2024), with potential consequences for the intensity and nature of contamination.

These shifts are already reflected in emerging contamination patterns. Occurrences of fumonisins and AFB1 in apple and apple puree, in addition to the expected PAT and *Alternaria* toxins (Carbonell-Rozas *et al.*, 2024), indicate increasing ecological plasticity of toxigenic fungi and potential contamination in previously unexpected host crops. In parallel, the capacity of *A. flavus* to adapt to fresh products, rather than being confined to low-moisture substrates, further highlights the evolving nature of the risks. Climate-induced abiotic stress may also reduce host resistance, increasing crop susceptibility and reinforcing links between plant health and mycotoxin contamination (Camardo Leggieri *et al.*, 2021).

These processes show transition from relatively predictable contamination scenarios towards more variable and system-dependent mycotoxin risk patterns. Evidence from Mediterranean agroecosystems illustrate this transition. The region, already characterized by high temperatures and recurrent drought, is a hotspot where climate-related pressures on crop systems are particularly evident. Since 2003 in Italy (Piva *et al.*, 2006), and subsequently in other European countries (Dobolyi *et al.*, 2013; Zmeu *et al.*, 2020; Pleadin *et al.*, 2023; Bilandžić *et al.*, 2025), AF contamination in maize has affected entire value chains, from primary production to animal feeding and dairy products. Similar concerns have been reported in Maghreb countries, where multiple mycotoxins, including AFs, OTA and ZEN, have been detected across a range of commodities, from cereals and dried fruits to spices and medicinal plants, with potential implications for consumer exposure under changing climatic conditions (Zinedine *et al.*, 2025).

These observations confirm that climate change is intensifying existing risks and expanding their geographic distributions and commodity ranges. In this evolving context, mycotoxin contamination should be interpreted as dynamic and systemic challenges, where plant health, environmental stress, and food–feed systems are closely interconnected. As highlighted by the maize paradigm, contamination cannot be considered as localized phenomena, but rather the results of processes that develop along the value chains, with implications for animal and human health. Increasing variability in fungal communities, host responses, and environmental drivers lead to heterogeneous and shifting risk patterns, challenging traditional approaches based on single hazards or static conditions.

Addressing this complexity requires shifts in research and hazard management strategies. Under climate change, the increasing variability and non-linearity of environmental drivers, together with shifts in fungal communities and host–pathogen interactions, make mycotoxin contamination less predictable and more system-dependent. Predictive modelling becomes essential for anticipating and interpreting these dynamics, as it enables integration of climatic drivers with crop physiology and fungal ecology, providing mechanistic understanding of contamination processes across temporal and spatial scales.

Examples include weather-driven and process-based models developed to predict the risks of *Fusarium*- and *Aspergillus*-related mycotoxin contamination in cereals, where meteorological conditions, crop phenology, fungal infection, and toxin production are considered during critical crop stages (Battilani *et al.*, 2016; Camardo Leggieri *et al.*, 2020). Under Mediterranean conditions, further model development should take better account for non-linear responses to temperature and water availability, the combined effects of heat and drought stress, shifts in crop phenology, and changes in the relative importance of competing toxigenic fungi, particularly *Fusarium* spp. and *A. flavus*. This would support gradual transition from static risk assessment towards more dynamic decision-support tools that anticipate changes in contamination patterns under climate change.

Key priorities therefore include development of predictive modelling approaches that integrate climatic drivers with crop physiology and fungal ecology. Extension of studies to broad ranges of crops and geographic areas, will provide improved understanding of mycotoxin co-occurrence, modification, and evolution along the value chain, from field to final products. More broadly, there is also requirement for adopting integrated plant health–food safety perspectives, supported by coordinated monitoring systems and strengthened international collaboration.

Chain-based and multi-actor approaches become essential, involving stakeholders across the entire agri-food system, and promoting intersectoral and multidisciplinary collaboration. Concepts of resilience, human and animal health, and broad geographical vision of food systems become key elements for addressing mycotoxin-related risks under climate change. Recent European initiatives, including MYMATCH and AMBROSIA, provide good examples of this direction, by promoting integrated approaches to food safety in changing climates, with emphasis on monitoring, data sharing, predictive tools, and collaboration among research institutions, risk

assessors, producers, and other actors in the food–feed chain (European Commission, 2024a; 2024b). Use of AI-based and data-driven tools, particularly when combined with biological knowledge and structured monitoring data, may support early detection of emerging risk patterns, and improve decision support under Mediterranean conditions. These initiatives may help translate system-level perspectives outlined in this review into operational strategies for anticipating and managing Mediterranean mycotoxin risks.

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